SEMI-ANNUAL STATUS REPORT

Structure and Dynamics of the Coronal Magnetic Field

NASA Space Physics Theory Grant NAG5-2257

5/1/93 to 10/31/93

submitted by

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This represents the *first* semi-annual Status Report on NASA SPT Grant NAG5-2257. During this period we have made progress on each of the four subtopics covered in our SPT proposal, and have produced one letter publication, two conference papers, and three papers in draft.

We have had two program-definition meetings with our principal consultant, Professor P. A. Sturrock (Stanford University), and summer research visits from Professor J. F. Drake (University of Maryland; magnetic evolution effects on the condensational instability) and from Professor G. Einaudi (University of Florence; Alfvén-wave dissipation and coronal loop instability).

A. The Quiet Corona

A.1. Heating by Current Dissipation

We have taken up the next phase of our investigation of the mechanism of coronal heating by dissipation of current filaments. We have now studied the response of a model *resistive* corona to random, long wavelength motions of the field-line footpoints (Parker 1972) using a three-dimensional, resistive MHD computer code. Approximate states of power balance have been achieved for values of the Lundquist number $S = 5 \times 10^4$, 10^5, 5×10^5, and 10^6, approaching the limit of computer capacity but significantly smaller than the coronal value of 10^{13}. In all cases, thin current filaments are observed to form in the corona in response to continuous motions of the footpoints. The thickness of these filaments is limited only by resistivity, and is numerically well resolved in all cases. Enhanced Ohmic heating results from the current filamentation. If a steady state is to be reached, the filaments will become as thin as required to dissipate the input Poynting flux. This input power is determined by the value of the transverse component of the magnetic field generated at the photosphere by the local footpoint motions. Thus, the question is not whether sufficient Ohmic power can be generated, but rather whether the plasma resistivity will allow the coronal field to become sufficiently stressed to accept the required input power. The power required to heat the quiet corona is

$P = 3 \times 10^5$ erg/cm^2/sec (Parker 1983). At $S = 10^6$, the input Poynting flux in our calculations is 5.6×10^4 erg/cm^2/sec, which is insufficient for coronal heating. From our calculations at various achievable values of S, we have deduced that this power scales approximately as $P \cong S^{0.2}$. Scaling to the coronal value of 10^{13}, we find $P = 1.4 \times 10^6$ erg/cm^2/sec, which is not only sufficient to heat the quiet corona, but is almost large enough for active region heating $\left(10^7 \text{ erg/cm}^2\text{/sec}\right)$. A paper on this research is in preparation for submission to *Astrophysical Journal*. We are presently studying the details of the plasma dynamics near the current filaments to determine the role played by tearing instabilities and magnetic reconnection.

A.2. Wave Coupling and Coronal Heating

We have begun to investigate the nonlinear coupling of Alfvén waves to other modes, such as magneto-acoustic waves, as a result of the inhomogeneous nature of the Alfvén speed in the solar atmosphere. The purpose is to understand the transport of energy from photospheric fluid motions to the corona. We plan to study the effects of wave heating with our 2-D radiative MHD code, which incorporates all of the necessary energy-transport contributions in an inhomogeneous medium, including thermal conduction, radiative cooling and heating. Because of the gravitational density variation, the Alfvén speed increases with height. We then launch pure Alfvén waves at periods ranging from 90 to 200 seconds from the coronal base in a simple, initially isothermal, atmosphere. When the wave amplitude exceeds approximately 0.3 × local Alfvén speed, it quickly couples into magneto-acoustic waves as it propagates upward. Because of the Alfvén speed gradient, the Alfvén and magneto-acoustic modes are both partially reflected from the high corona. However, it was discovered that the energy deposition into the plasma, i.e., the heating, is primarily due to the compression of the magneto-acoustic waves in conjunction with the effects of thermal conduction. This is in contrast with the case of the resonant absorption of Alfvén waves in a medium with transverse gradients (Mok and Einaudi 1990). This compressional-heating mechanism will be further studied in a medium with a longitudinally varying magnetic field, such as an open-field region, where the diverging magnetic field is expected to enhance the coupling and reflection of the waves, resulting in more energy deposition into the coronal plasma.

A.3. Thermal Structure of the Magnetized Solar Transition Region

An understanding of the thermal structure of the transition region (TR) in the solar atmosphere is fundamental. The sharp temperature and density gradients in this narrow region provide an essential energy-flux connection between the hot corona and the cool chromosphere. Although the physics of the upper TR is reasonably well understood, the thermal structure predicted by conventional theories disagrees with observations in the lower TR. At higher temperatures, the thermal structure can be predicted by balancing the heat absorbed by the coronal plasma with the divergence of the heat flux parallel to the local magnetic field. The predicted differential emission measure (DEM) agrees reasonably well with observations. However, in the lower TR, a model that assumes balance between the same heat flux and the radiative energy loss results in a DEM qualitatively different from observations. What is apparently needed is a strong contribution from perpendicular (to **B**) thermal conduction (Rabin 1986).

With this requirement in mind, and stimulated by our recent work on prominence condensation and levitation (Drake *et al.* 1993), we have investigated the transition-region structure of a magnetic arcade. We studied this possibility in detail by numerically integrating the radiative magnetohydrodynamic equations, including the effects of gravity and of the distortion of magnetic field lines due to plasma flow. By starting with a current-free arcade field, we let the plasma settle into an equilibrium with dynamic balance between gravity, magnetic forces and pressure gradients. We were thereby able to obtain a self-consistent thermal structure for the quiet sun with point-to-point energy balance from the hot corona to the cool chromosphere. The predicted DEM agrees with observations quantitatively (Van Hoven and Mok 1993). The fundamental difference between this result and the conventional field-free or vertical-field models is that the magnetic loops in the center of the arcade, below a critical length

(Mok *et al.* 1991) unstably drop to chromospheric temperatures. Near this critical field line, there is a large perpendicular temperature gradient at the same time that the parallel thermal conduction drops because $\kappa_{\parallel} \sim T^{5/2}$ drops rapidly. The thermal structure, therefore, is determined by the balance of the divergence of the downward, perpendicular, heat flux and the radiative energy loss. In the temperature range of the lower TR, the DEM is $\sim T^{-7/2}$ averaged over the entire arcade (Van Hoven and Mok 1993). We now believe that the thermal structure of the lower transition region in the quiet sun is understood.

B. The Active Corona

B.1. Loop Evolution and Dynamics

During this grant period we have begun a collaboration with our colleagues at the University of Florence, Dr. Giorgio Einaudi and Dr. Marco Velli, who are experts on ideal and resistive MHD stability in the solar context. The goal of the collaboration is to explore the ideal and resistive MHD properties of coronal loops. In particular, Drs. Einaudi and Velli, with the help of a graduate student at the U. of Florence, will use a 3D MHD code developed at SAIC to explore the nonlinear properties of the kink mode. The key question to be studied is whether the nonlinear development of the kink instability in a loop causes current sheets to form. The equilibrium and linear stability properties of kink modes were studied with this code by Mikić, Schnack, and Van Hoven (1990). Einaudi and Van Hoven (1981, 1983), Hood and Priest (1981), and Velli, Einaudi, and Hood (1990) have also investigated the linear stability of coronal loops. The study of the nonlinear behavior of the kink mode has been initiated by Mikić (1990) and Craig and Sneyd (1990).

During the period October 11-15, Drs. Dalton Schnack and Zoran Mikić of SAIC met with Drs. Einaudi and Velli at the Scuola Normale Superiore in Pisa, Italy. During the week of discussions a plan was laid out on how to approach the study of the nonlinear evolution of the kink mode. It was decided to use the 3D MHD code (named "MAC") developed at SAIC to continue simulations of the kink mode at the U. of Florence. The code is presently being converted to the UNICOS operating system (used by CRAY supercomputers), and will be delivered shortly to Florence for use on this problem. Progress in this task will be reported in the next Semi-Annual report.

We have also developed a new cartesian MHD code to study the 3-D formation of coronal loops as a result of vortex motions in the photosphere. The initial condition consists of a potential magnetic field whose normal component on the photosphere can be arbitrarily specified. A fluid flow pattern on the photosphere, such as a vortex, can then be applied at the lower boundary. Initial results show that two vortices with the same rotational direction on the photosphere can twist the potential magnetic field to form a loop-like (semi-toroidal) structure rising from the surface. Further evolution and diagnosis of these structures is being pursued.

B.2 Dynamic Boundary Conditions at the Coronal Base

The dynamic "line-tying" boundary condition at the interface between the corona and the chromosphere has been controversial. Although a complete picture must include the effects of the narrow, but finite, transition region, heuristic assumptions used in many analytic models often treat the interface as a sharp boundary to simplify the calculation. Without detailed knowledge of the behavior of the transition region, one often tends to use simple "boundary conditions," such as "rigid wall," "line-tied," and discontinuous density, based on various arguments. Since these boundary conditions have different implications, we have made a 1.5-D numerical study to investigate the actual response of a realistic chromosphere to dynamic activity in the corona. Our study incorporates not only the dynamics but also the energetics of the atmosphere, including radiative cooling and thermal conduction which result in a realistic transition region acting as a buffer between the hot, tenuous corona and the cool, dense chromosphere. A 1-D equilibrium with dynamic and energetic balance is perturbed in the corona with longitudinal and transverse perturbations. For longitudinal perturbations, the fluid velocity is measured in the corona and the chromosphere as the acoustic wave propagates downward. We found that the response in the chromosphere is not negligible even though its density is two orders of magnitude higher than the corona. The "rigid wall" boundary condition is clearly not appropriate. We studied a series of equilibria with different corona-to-chromosphere temperature ratio, and found that the responses scale like acoustic speed but with an amplitude bigger than the one predicted by the discontinuous-fluid model. For transverse perturbations, the 1.5-D equations, with perpendicular velocity and magnetic field, are advanced in time as detailed in our previous work (Van Hoven, Mok and Drake 1992). A magnetic perturbation is excited in the corona, and perpendicular fluid displacements are measured in both the corona and the chromosphere as the Alfvenic perturbation propagates downward. The fluid displacement in the chromosphere is found to be significant and, again, the "rigid wall" boundary condition is invalid. A series of parametric studies shows that the responses scale according to Alfven speed. As in the longitudinal case, the amplitude of the response is bigger than predicted by the discontinuous-fluid model.

B.3. Dynamic Prominence Initiation

A continuing mystery about the formation of filaments and prominences is the character of the mechanism, whether instability or loss of equilibrium, for the initiation of the cooling condensation. We have attacked this problem with a new magnetic-evolution process suggested by the observations of Martin (1992). In this scenario, a magnetic arcade is so strongly sheared (by differential photospheric flows) that two short loops reconnect into a longer loop. This process has two positive physical effects: it strongly reduces thermal-conduction losses to the chromosphere, and it provides a dense and cool seed (at the reconnection point) for the subsequent filament condensation.

We have now taken up this problem in a model form in 2D, using a dynamic simulation code which can provide a magnetized, gravitating, solar atmosphere (similar to that described in Sect. A.3), including two current-free arcades. The opposite-polarity central legs of the arcades are then pushed together by surface (lower boundary) motions until they reconnect and begin to rise because of magnetic tension forces. This model problem is currently running through the reconnection phase, and we are continuing to study the subsequent levitation and condensation phase.

C. Magnetic Energy Release and Transport

An outgrowth of our coronal heating project (Sect. A.1) is a program to comprehend the Parker (1972, 1983) magnetic-dissipation mechanism. That is, does the exponentially increasing current density (Mikić *et al.* 1989) arise from very fine filaments which decay resistively, or from current sheets which may dissipate dynamically through reconnection?

Our 3-D simulations now indicate that the dissipation occurs in the form of quite elongated current sheets, as shown in Fig. 1. Thus, we are studying these irregular structures in

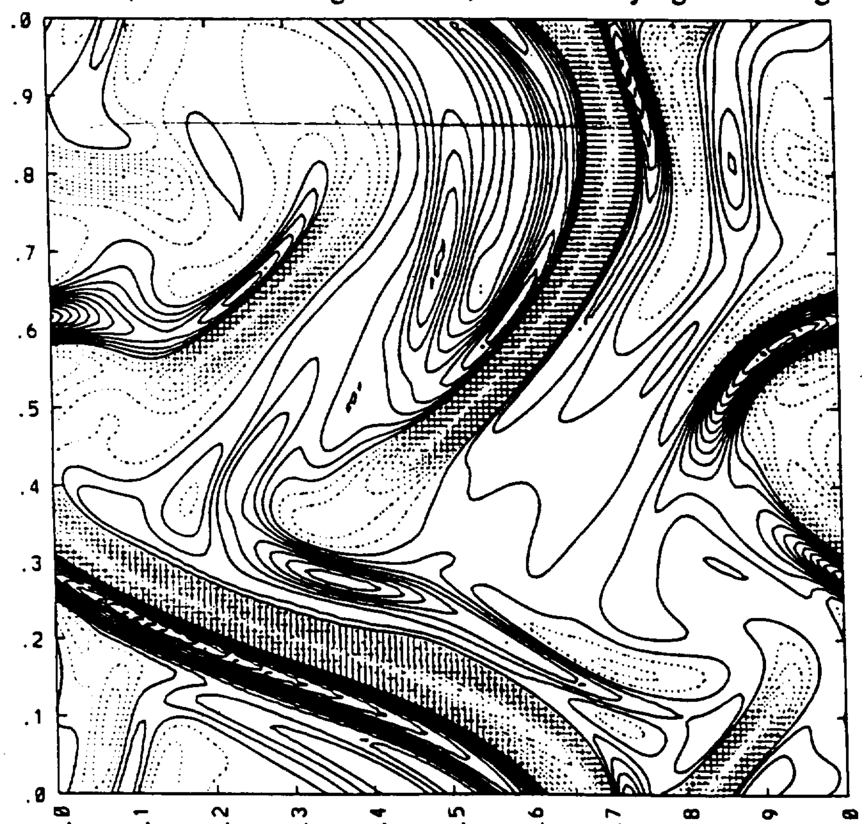

Fig. 1. Axial-current-density contours at the apex of a (straightened) coronal magnetic "loop" structure. This is an $S = 10^6$ resistive realization of the Parker (1983) heating model in which the field lines are randomly stirred (on the transverse scale ℓ of the box) at their line-tied ends. Note that the current sheets often appear in multiple layers and that the narrowest one is $\sim 0.057\ \ell$ in width and $\sim 1.6\ \ell$ in (transverse) length.

the context of 3-D magnetic reconnection (Schindler *et al.* 1988, Strauss 1991). To do so, we are evaluating a number of reconnection and tearing-mode diagnostics, particularly concentrating on the spatial structure, with some promising results.

D. Energy Transport in the Solar Wind

Our first time-dependent hydrodynamic models of the solar wind are based on a one-dimensional fluid-dynamics code developed to study quasar emission and absorption clouds (Schiano, Christainsen, and Knerr 1993, *Ap.J.*, in press). Originally designed as a test-bed program to study the effects of boundary conditions on higher dimensional flows in the aforementioned project, it is highly effective and accurate for solving time-dependent flows with shock waves, radiative effects, and varying geometrical grids. This code is based on the Norman-Wilson second-order-accurate scheme and employs operator splitting, van-Leer monotonic advection constraints, tensor artificial viscosity (for the non-Cartesian grid problems), and a variety of boundary conditions (including Thompson non-reflecting boundary conditions).

To adapt the code to the solar wind problems we are investigating, we began by adopting a one-dimensional spherically-symmetric geometry incorporating variable grid-cell sizes, which allows for enhanced numerical resolution near the solar surface and chromosphere. At a large radius (currently 100 solar radii - well beyond the sonic point in the outflow) we apply extrapolative boundary conditions that allow the wind to flow smoothly out of the numerical mesh without causing spurious reflections. With these modifications, we tested this code directly against a steady-state, adiabatic, Parker-type, solar-wind solution, which we interpolated onto the numerical mesh in the hydrodynamic code. Due to the finite resolution of the code, small differences between the initial conditions and the true steady state develop as small-amplitude shocks that propagate out of the computational domain. After these transients disappear, the code settles into a stable, steady solution very close to the exact Parker-type solution.

Following this success, we incorporated thermal-conduction effects into our hydrodynamics code using the standard Spitzer formula for the plasma conductivity. While the algorithmic basis of the fluid code is explicit in nature, we choose to solve for thermal conduction using an implicit numerical algorithm in order not to constrain the size of the time-step even more than the Courant time. As such, the code now consists of two operator-split segments: an explicit hydrodynamic step followed by an implicit thermal-diffusion step.

We then made a direct comparison of our time-dependent code with a steady-state solar wind model that includes thermal conduction. This test is illustrated in Figure 2. A small perturbation generated near the solar surface propagates outward as a shock and passes smoothly

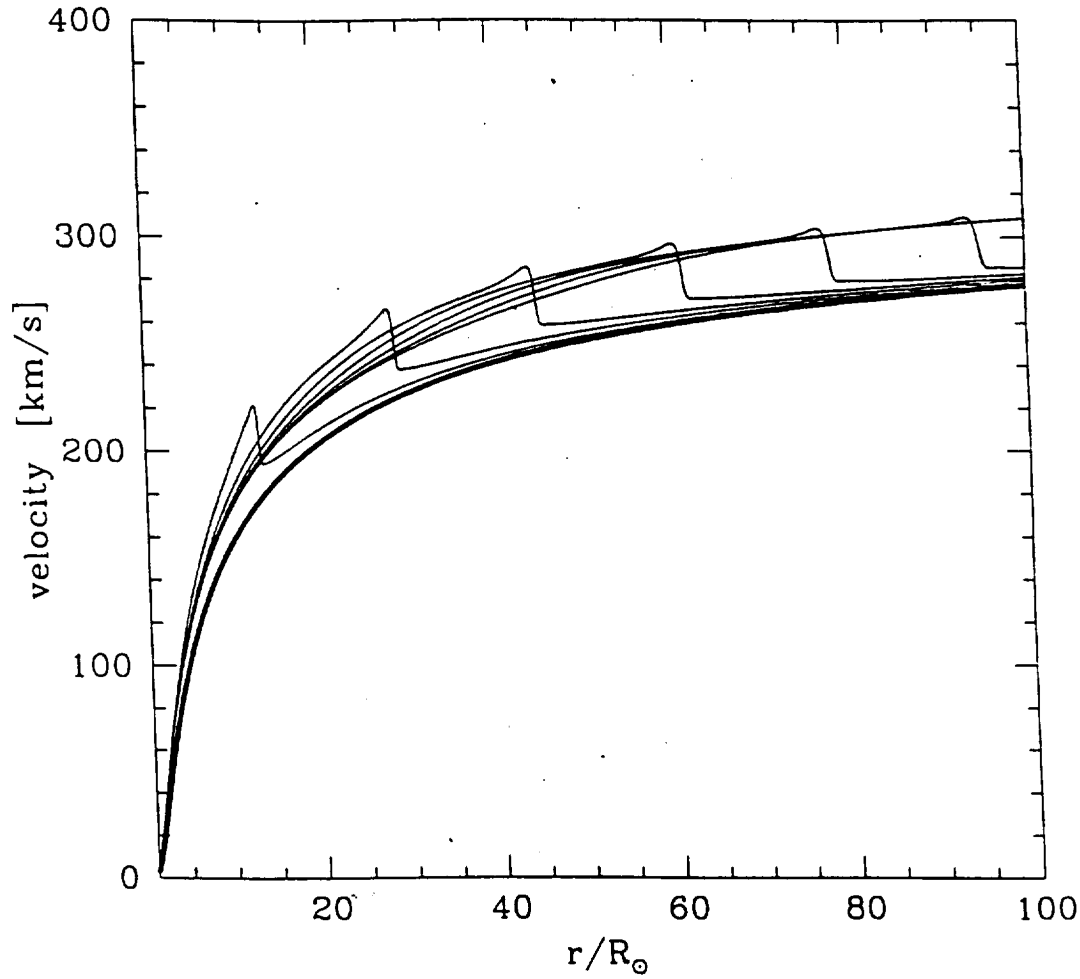

Fig. 2. Velocity versus radius for a spherically symmetric solar wind including thermal conduction. The heavy curve is the velocity profile at t=0. The other curves are separated by $t = 3.2 \times 10^4$ seconds. A relatively weak, nearly isothermal shock develops near the solar surface and propagates outward with a speed of 360 km/s. After it leaves the outer boundary (at 100 solar radii), the resulting wind solution is in a steady state (upper smooth line).

through the outer boundary, leaving behind no artificial numerical oscillations. After this transient leaves the computational domain, the solar-wind solution settles into a steady state. We have tested the code using a variety of boundary conditions and have found it to be very robust.

Our next step is to modify the code to include multiple interacting fluids: one for protons, one for electrons, and (eventually) one for alpha particles. Thermal conduction and collisional interactions among the species will be incorporated. With this code, we will be able to attack time-dependent solar wind problems, such as the propagation of coronal disturbances into an initially steady wind.

E. Publications Supported by NAG5-2257 (Abstracts Attached)

1. The Differential Emission Measure of Nested Hot and Cool Magnetic Loops, Solar Phys. Letts **147**, 199 (1993); G. Van Hoven and Y. Mok.

2. The Generation of Solar Magnetic Activity, in Proceedings of the NSO/SPO Workshop on *Solar Active Region Evolution* (K.S. Balasubramaniam and G. W. Simon, eds.), to appear in Publ. Astron. Soc. Pac. (1994); G. Van Hoven, D.D. Schnack, Z. Mikić and J.A. Linker.

3. Current Filaments Induced in a Resistive Corona by Continuous Footpoint Motions, in Proceedings of the NSO/SPO Workshop on *Solar Active Region Evolution* (K.S. Balasubramaniam and G. W. Simon, eds.), to appear in Publ. Astron. Soc. Pac. (1994); D.D. Schnack and Z. Mikić.

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Van Hoven, G., and Mok, Y. 1993 *Solar Phys.* **147**, 199.

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THE DIFFERENTIAL EMISSION MEASURE OF NESTED HOT AND COOL MAGNETIC LOOPS

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Abstract. The detailed thermal structure of the magnetized solar transition region, as measured by its *differential emission measure* [DEM(T)], is poorly known. Building on the fact that the solar surface is strongly magnetized and thereby structured, proposals have been made that envision a significant lower-temperature contribution to the energy balance from (ion) heat flux *across* an arcade of different temperature loops. In this paper, we describe a *self-consistent*, 2-D, MHD simulation, which includes the full thermal effects of parallel stability and anisotropic conduction, of a nested-loop model of the thermal and magnetic structure of the transition region. We then demonstrate that the predicted DEM agrees with observations in the conceptually elusive $T < 10^5$ K regime.

1. Introduction

The transition region (TR) in the solar atmosphere provides the essential energy-flux connection between the heat-deposition layers of the high-temperature corona and the strongly radiating layers of the cool and dense chromosphere. ~~The thermal structure of the upper~~ TR (from 10^5 to 10^6K) is reasonably well understood to result from approximately constant conductive (electron) heat flux parallel to the magnetic field (Pallivicini *et al.* 1981, Athay 1981). However, the structure of the *lower* TR (10^4 to 10^5K) has eluded theoretical interpretation for a long time (Athay 1966, Gabriel 1976, Rabin 1986). First, the balance between heating, radiation and the divergence of the heat flux in the lower TR is fundamentally different from that above 10^5 K. Second, for $T < 10^5$, the effects of *cross-field* (ion) heat conduction can become important.

One informative measure of the TR's thermal structure is the differential emission measure, which is commonly observed and derived as a function DEM(T) of the temperature $T(s)$ [assumed monotonic along the observed line of sight s]. A simple treatment of the potential effects of cross-field heat flux on the low-temperature DEM has been given by Rabin (1986) who considers isotherms tilted at a small angle to the (uniform) ambient magnetic field. Structured TR models have been proposed by Rabin and Moore (1984) who suggested that the lower-TR radiation comes from narrow current filaments which dissipate their energy by perpendicular thermal conduction, and by Antiochos and Noci (1986) who suggested that the solar DEM can be reproduced by a careful assemblage of magnetic loops with a selected maximum-temperature distribution and a lower-TR temperature-gradient scale set by gravity. A recent paper by Mok and Van Hoven (1993) has demonstrated, via numerical simulation, a quasi-vertical-field model which is structured by heat-input variation, as originally proposed by Athay (1990), that exhibits the correct full-temperature-range variation of the DEM. [This earlier publication also discusses more of the background than can be included in this brief letter.]

The present investigation is motivated by a number of aspects of these earlier conceptions of the conductive effects of magnetically structured loops and of their thermal stability. We propose a nested-loop (or arcade) model of the TR, which we examine *via* a computational solution of the magnetohydrodynamic (MHD) equations including energy transport. We thereby obtain the *self-consistent* magnetic and thermal structure of this model TR and then compute the differential emission measure over the full range of temperature for comparison with observations.

The fundamental difference between this work and Mok and Van Hoven (1993) is the magnetic geometry, which shapes the thermal structure *via* the juxtaposition of cool and hot loops dictated by thermal stability (Mok *et al.* 1991), and controls the anisotropic heat flow in the atmosphere.

Solar Physics **147**: 199–202, 1993.

The Generation of Solar Magnetic Activity

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Abstract. Most of the activity of the sun arises from the release of magnetic energy, which is injected into the atmosphere via eruption and convectively driven stresses. We briefly detail the boundary coupling, between photospheric flows (possibly due to sub-surface drives or eruptions) and coronal fields, by which convective motions and differential rotation can drive the line-tied evolution of closed magnetic structures. We then describe several examples of MHD simulations of these energization and dissipation/eruption phenomena, with some emphasis on the evolution and instability of coronal loops.

1. Introduction

During the last decade there have been significant quantitative advances in observations and theory which have added considerable substance to older qualitative ideas about the development of magnetic activity on the sun.

The basic physical concept is that the solar magnetic field erupts into the atmosphere in a *relatively* unstressed (weak current flow) state; it is then progressively twisted and stretched by the non-uniform vortical and shearing motions of the convective solar surface, in which the ends of the field lines are quasi-rigidly imbedded (line tied) because of the high plasma conductivity, as illustrated in Fig. 1.

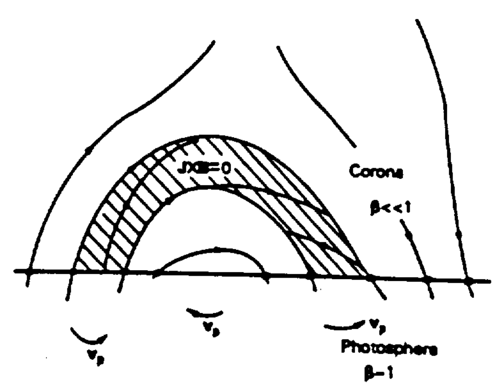

Fig. 1 A schematic view of the coronal fields which are line-tied (junction dots) to the photospheric flows and thereby energized (from Browning 1991).

Current Filaments Induced in a Resistive Corona by Continuous Footpoint Motions

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Abstract. The response of a model resistive coronal plasma to slow, continuous, long length scale photospheric motions is calculated with a three-dimensional MHD code. Values of the Lundquist number S between 5×10^4 and 10^6 are used. It is found that a filamentary current structure forms and persists dynamically. The current filaments are thinner for larger S. No evidence of instability of these current filaments has been observed. These current filaments result in an enhanced Ohmic heating rate. Scaling laws for input and output power of the form S^{ν} have been determined. For Ohmic power, we find $\nu = 0.2$. This allows sufficient power to heat the quiet corona at $S = 10^{13}$.

1. Introduction

The mechanism that heats the closed regions of the corona is unknown. The coronal magnetic field is anchored in the dense photosphere. Convective motions occur in the photosphere with length scales of approximately $l_v \approx 10^4$ km. These motions cause the footpoints of the coronal magnetic field lines to be randomly shuffled on this length scale. These motions of the footpoints induce electric currents to flow in the corona. If these coronal currents retain the same transverse scale length as the driving photospheric flow, then the coronal resistivity is too low for conventional Ohmic dissipation to produce the power required to heat the corona. However, it is possible for the Ohmic power to be considerably enhanced if the coronal current instead flows in very thin filaments. According to one model (Parker 1972), the corona can be heated by resistive dissipation of electric current filaments that are induced by the long wavelength random twisting of the coronal magnetic field (Parker 1972; van Ballegooijen 1985). The viability of this method of coronal heating requires that the current filaments attain a transverse scale length of $l \approx 10$ meters. Theoretically, the question is twofold: can filamentary current structure form naturally from smooth, long